On Bending Capacitis of 6″ and 12″ Spool Bends in Deep Water

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Abstract

This paper presents a bending capacity study to 6″ MEG and 12″ production flowline spool bends. Various design criteria for assessing the bending capacity of spool bend have been investigated. Based on detailed disucssions, a combined criterion is concluded finally, in which sufficient safety margin and as well as the acceptable ovality are both considered. In this study, the spool bending capacity assessment comprises of three parts. Firstly, the local non-linear finite element model of the spool bend is analysed by the implicit solver cooperated in LS-DYNA. The bend capacities are established based on the combined criterion concluded in this paper. Secondly, the global finite element model of the whole spools are analysed by ANSYS 13. The global model is only considered in linear regime. All practical loading cases during the spool's service time are included. The actual loading for the spool bends under different loading cases are summarized. Finally, the results from global and local models are compared with each other. The bending capacity check is done by making sure that the actual loading of spool bend from the global model is no bigger than the bend capacities obtained from the local numerical model. Quite a few numerical simulations have been carried out. Conclusion remarks are summarized at the end of present paper.

Keywords

Bending Capacity; Spool Bend; Deep Water; Finite Element Analysis

Introduction

This paper presents a bending capacity study for spool bends of 6″ MEG and 12″ production spool. Rigid spool bends are widely used in subsea and pipeline engineering due to their flexibilities. However, there is lack of design regulations regarding the design of spool bends; see DNV (2011). Until now, bends have typically been suggested to be designed based on stress based criteria; see ASME (2006, 2007) and DNV (2012). To cope with the subsea system development under deep water area, the spool bends are designed to allow moderate plasticity development occasionally, where the stress based criteria doesn't apply. In such case, a robust and reasonable strain based criterion is crucial for the bending capacity assessment, which put necessarity to present study.

Based on DNV (2012), the local buckling check for spool bends should include following aspects in general:

- No potential for collapse
- Sufficient safety margin on bending capacity
- Imposed ovality is acceptable

The collapse check could be done by calculating the characristic pressure which is the same as the straight pipeline defined in DNV (2012). The possible corrosion of the bend should be considered during the collapse check. The challenging part is to find a robust and reasonable design criterion to make sure the bend has sufficient safety margin on bending capacities during its service time. And the imposed ovality should be acceptable, for instance, the internal "pigging" check requirement for the ovality.

Von Karman (1911) and Rodabaugh and George (1957) developed analytical approach to pipe bend under elastic deformation, which are based on the principle of minimum strain energy. "Ideal" assumptions are made in order to derive the analytical solutions and thus it is not straightforward to apply such methods. The same question also applies to the work done by Gresnigt (1959) and Boyle (1981).

Gresnigt (1986) pioneers the study on the plastic design method for pipe bends under settled areas; both analytical and numerical models are proposed. The moment-angular diagrams of bend under both in-plane and out-of-plane moment with internal pressure loadings are presented and further discussed, which gives fundamental understandings about the bending mechanism of pipe bends. However, more complicated loading combinations, such as the external hydrostatic pressure with in-plane moment is not considered.

In practical cases, nonlinearities on geometry and material properties should be both included in the analyses, which put a big challenge to the analytical solutions. Up till now, the bending capacity for pipeline bends is generally analyzed by finite element methods. Two failure modes, namely "open" and "close" are usually adopted. A typical moment-displacement curve as shown in Fig. 1 is generated and used to describe the bending moment capacity.

Chattopadhyay (2006, 2007) has concluded analytical approaches to the capacities of the pipe bend under internal pressure loading. The criterion called "TES" (twice elastic slope) has been used. The existing of internal pressure stabilizes and increases the bend capacity, which is the main argument for the use of TES criterion in Chattopadhyay's works. As to spool bend in deep water, the loading case with external water pressure makes the bend collapse more easily. The "TES" criterion may point to the post-collapse strength; see Fig. 1. Thus it may be not appropitiate to apply "TES" criterion.

Pappa et. al (2008) examined the capacity of pipe bends under in-plane and external/internal pressure loadings by numerical finite element simulations. It is concluded that the presence of internal pressure is beneficial for spool bends while the external pressure reduces the capacities. However, no design recommendations are explicitly suggested for the measurement of the capacity of pipe bends.

Liu (2010) presents a method where the DNV-OS-F101 regulations (see DNV, 2007) for straight pipes and the non-linear finite element analysis (NLFEA) for pipe bends are combined to check the pipe bending capacity. The collapse bending moment for spool bends obtained from NLFEA together with a safety factor of 0.75 are used to obtain the allowable bending moments. But the ovality check has not been considered in his approach.

Bjerkås et. al. (2010) shows the investigation of pressure-moment curve for pipe bends under different design criterion, which forms the basis for present study. The TES criterion gives the maximum highest bending moment capacity of bends when the external pressure is not significant. The 3 % allowable ovality gives about 50 % lower capacity compared to TES criterion. If the external pressure is significant, 3 % ovality criterion gives larger capacity comparing to TES. The criterion based on 0.2 % allowable strain gives the lowest moment capacities. 'strain' here means the equivalent strain at the upper surface of the cross section

To summarize, the following criteria are chosen as the candidates for the determination of the allowable range for the bending moment capacity of the spool bend. Their relative positions on the moment-displacement curve are presented in Fig. 1. The locations for upper and mid surfaces are illustrated in Fig. 4.

- 0.2 % equivalent strain at the upper surface of the crosss section, where the outer fiber of the bend is located;
- 0.2 % equivalent strain at the mid surface of the cross section, which is the center place of bend wall thickness;
- Maximum bending moment/TES criteria (the TES criteria applies when the "hardening" of moment curve happens. It may go to infinite value mainly due to the strengthened stability of the bends by the internal pressure.);
- 0.2 % axial strain at the upper-surface;
- 5 % ovality as the maximum ovality for pigging inspection (ASME, 2006).

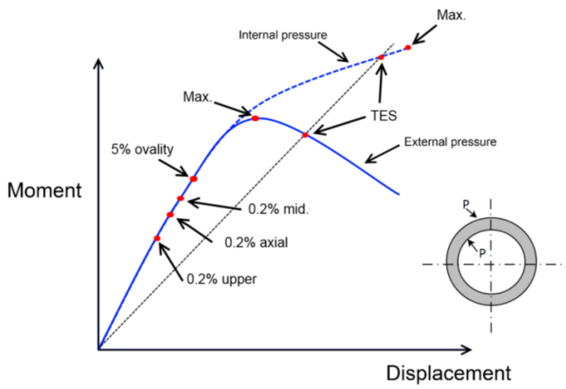

FIG. 1 DIFFERENT CRITERIA POSITIONS ON MOMENT-DISPLACEMENT CURVE. (NOTE THAT THE REALTIVE LOCATIONS MAY BE CHANGED DUE TO VARIOUS LOADING CONDITIONS)

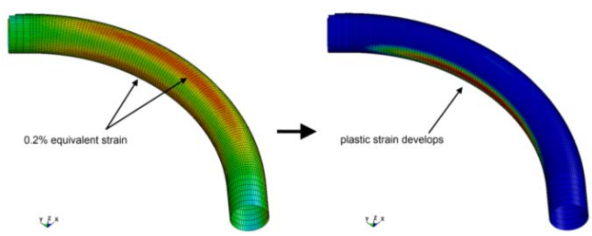

FIG. 2 EQUIVALENT AND PLASTIC STRAIN AT BEND.

The "equivalent strain" in this study is computed based on following equations:

$$\varepsilon_{eq} = \frac{2}{3}\sqrt{\varepsilon_1^2 + \varepsilon_2^2 + \varepsilon_3^2 - (\varepsilon_1\varepsilon_2 + \varepsilon_2\varepsilon_3 + \varepsilon_3\varepsilon_1)} \qquad (1)$$

where ε_1 is the hoop strain, ε_2 is the axial strain and ε_3 is the through thickness strain. Notice that ε_3 here is not computed based on elastic relationship with ε_1 and ε_2 as previous work did (Bjerkås, 2010). The reason to this is that the strain based criteria as mentioned above will produce plastic deformation to the bend, where the linear relationship does not apply; see Fig. 2.

Present paper is a continuation of previous work (Bjerkås et.al, 2010). However, comprehensive discussions regarding the bend strength criteria are performed. The combined criterion was finally concluded as the final criteria to calculate the "right" capacities for bends. The actual bending moments for bends in the global numerical model are compared with the corresponding capacities. Thus, the bending capacity check for spool bends is achieved.

Local Model

General

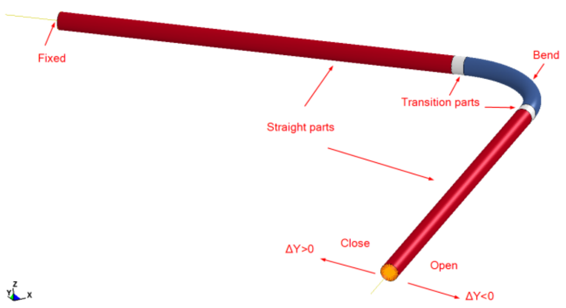

FIG.3 LOCAL FINITE ELEMENT MODEL OF THE 6" INDUCTION SPOOL BEND

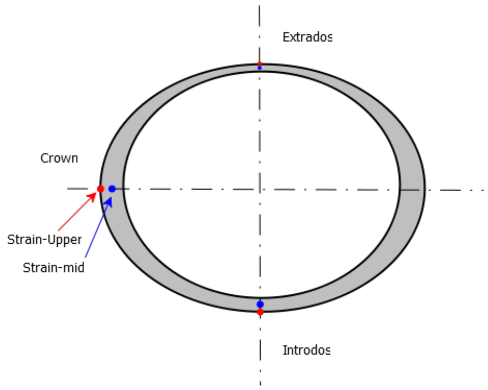

FIG.4 LOCATIONS FOR THE CRITERIA SCREENING

The numerical simulations for the local spool bends have been performed by using the implicit feature of the commercial code LS-DYNA; see Hallquist (2007). The same model as presented in Bjerkås et. al. (2010) has been used, which has been validated with full scale experiment tests. For the present study, modification was made accordingly based on present spool's dimensions.

Only in-plane bending moment is considered in present study. The prescribed displacement is applied to one of the bend ends, while the other one is fixed. Two modes for failure have been simulated by implicit code LS-DYNA with displacement controlled method, namely "close" ($\Delta Y > 0$) and "open" ($\Delta Y < 0$); see Fig. 3.

The bend model is comprised of three parts, the bend, the transition parts and the straight parts. Initial ovality was applied to the bend part of the model.

Three locations from the bend centre area are picked for criteria screening, namely the extrados, intrados and the crown; see Fig. 4.

The differential pressure applied to the pipe bend was based on the actual values during the bend's service time according to company's engineering experience.

Four material properties have been used in the simulation, see Fig5. MAT_024 in LS-DYNA material library is used. Note that only the plastic part of the curve is plotted in this Fig. 5, the elastic part is automatically computed by the code, Hallquist (2007). MAT2 and MAT3 in Fig.5 are applied to the transition and straight parts respectively.

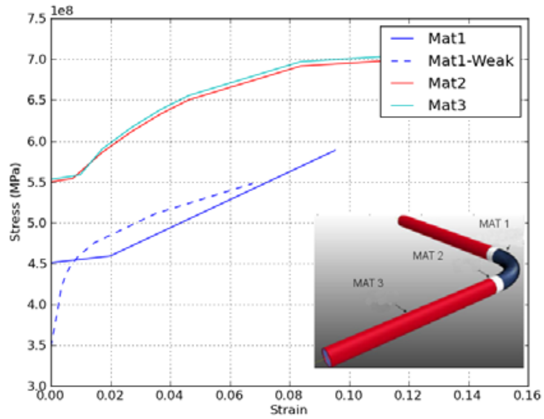

FIG. 5 MATERIAL CURVES (PLASTIC PART) AND AN EXAMPLE OF THEIR LOCATIONS

The dimensions for the 6" MEG and 12" production flowline bends are listed in following table.

TABLE 1 BEND DIMENSION FOR 6" MEG AND 12" PRODUCTION SPOOL

PARAMETERS	6"	12"	UNITS
OD	168.3	323.9	mm
Thick nom	9.9	16.1	mm
Thick min	8.91	14.49	mm
Thick max	10.89	17.71	mm
Bend angle	90,45	90,60,30	°
Ovality	3%	3%	-
Material No.	MAT1 MAT1-Weak	MAT1	-

Criteria for Bend Capacity

To a give a general impression of the candidate criteria as mentioned earlier, a case study was performed firstly. Three typical loading differential pressures and the MAT1-Weak were applied to the 6" MEG 90 deg bend model, which are -92.2 Bara, 0 Bara and 260 Bara. Bending moment curves from the LS-DYNA spool bend evaluations at various pressure states are presented in Fig. 6. Indications at which bending moment level corresponds to the various criteria are plotted by the colored dots. It is fairly clear to see that the three strain based criteria have enough safety margins to collapse especially when the bend is under external pressure loading. It is recommended that these three are all safe to be used in design.

As to the MAX-TES criterion, it generally gives the maximum bending capacity comparing to other critera. As seen in Fig. 6, the bending capacities obtained by MAX-TES are no less than the ones obtained by 5 % ovality criterion, which means that the corresponding ovality of the bend under MAX-TES criterion will exceed 5 %. According to ASME (2006), the pigging requirement for the pipe bend is jeopardised.

The 0.2 % equivalent strain at upper-surface yields the most conservative capacities comparing to other strain based criteria, especially when the internal pressure is significant high in "open" mode (left side in Fig. 6), in which the local reshaping mechanism contributes significantly to the equivalent strain; see Fig. 7. To give more details, Fig. 8 presents the ratio between equivalent strain at upper and middle surface under different pressure loadings in a "worst" case ever tested. It is clearly seen that huge difference exists at the beginning of the loading when the internal pressure is significant. The extremely high ratio value is due to the small values of equivalent strain at middle surface at the beginning. Capacity problem may arise in such case since quite low capacity obtained if this criterion is used.

The local reshaping happens when the internal pressure is high. As seen from Fig. 7, the outer fibre takes relative large local deformation comparing the middle one. This local effect will not influence the overall deformation of the bend since the corresponding ovality is less changed. However, the gradient of strain across the pipe wall increases significantly due to this fact. The 0.2 % equivalent strain at upper surface is not valid to represent the bend moment capacity because it is shadowed by the reshaping. Hence, more attention should be paid to the usage to this criterion since quite conservative capacities may be obtained.

The criterion of 5 % ovality describes the deformation of the bend under loading. In "open" mode, the ovality is decreased in the beginning of the load since the opening of the bend "smooth" the spool bend to some extent. And after that, the ovality increases as the displacement increases. Thus, the criterion of 5 % ovality may give quite high bending moment capacities, in which that the pipe bends became plasticized over a large area, see Fig. 6. On the other side, this criterion may yield very conservative results in "close" mode when external pressure applied, see Fig. 6. It is quite necessary to involve the ovality criterion into the practical bend design.

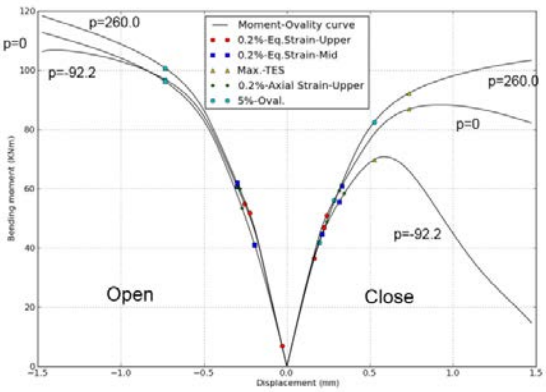

FIG. 6 MOMENT-DISPLACEMENT CURVE WITH CAPACITY VALUES UNDER DIFFERENT CRITERIA WITH MAT1-WEAK FOR 6" MEG 90 DEG BEND

The other two strain based criteria, 0.2 % equivalent strain at mid-surface and 0.2 % axial strain at upper surface produce close bending capacities when the pressure loading is not significant. The reason is that the local reshaping doesn't play an important role in such cases. However, they may yield different capacities when the pressure loads present; see Fig. 9 and 10.

In this study, a compromise was made by considering both criteria to generate the bending capacity curves for the bend. It is proposed in this paper that the moment capacity of the bend should be based on the capacity values obtained by 0.2 % equivalent strain at mid-surface, 0.2 % axial strain at upper-surface and also the 5 % ovality. The most conservative values from these three criteria should be used as the capacity value for the bend. By doing this, enough safety margins and the pigging requirement are both satisfied. The proposed method could be presented by following equation:

$$M = min(M_{0.2\%-mid}, M_{0.2\%-axial}, M_{5\%-ovality}) \quad (1)$$

Where M is proposed bending capacity, $M_{0.2\%-mid}$ is the bending capacity obtained based on the criterion of 0.2 % equivalent strain at mid-surface, $M_{0.2\%-axial}$ is the bending capacity obtained based on the criterion of 0.2 % axial strai at upper surface and $M_{5\%-ovality}$ is the bending capacity obtained based on 5 % ovality criterion.

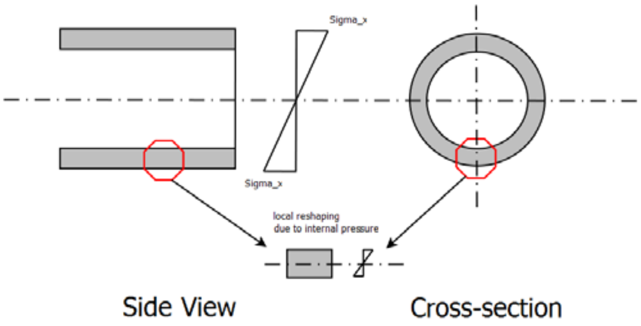

FIG. 7 LOCAL RESHAPING MECHANISM

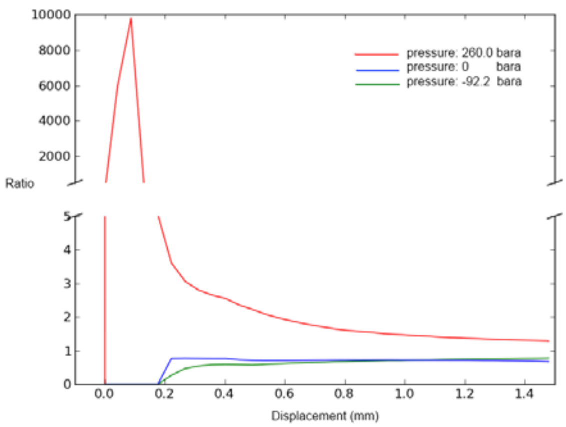

FIG. 8 RATIO BETWEEN EQUIVALENT STRAIN AT UPPER AND MIDDLE SURFACE UNDER DIFFERENT PRESSURE LOADING FOR 6" MEG 90 DEG BEND (MAT1-WEAK).

Bend Capacity Curves

The pressure-moment curves are presented based on those candidate criteria together with the new proposed capacity curve; see Fig. 9 and Fig. 10. Notice that all the curves plotted in these two figures are calculated by 3 order polynomial fitting to the raw data from local finite element analyse. The positive moment denotes "open" mode while the negative moment denotes "close" mode in present study.

As seen from Fig. 9, the 0.2 % equivalent strain at upper-surface gives generally the most conservative capacities in all loading cases. A dramatic capacity drop can be observed in the "open" mode when the bend is under internal pressure loading, which has been discussed in details previously. And on the opposite, the MAX-TES yields the least conservative capacities. To handle all loading condtions, it is not recommended to use only one criterion and the combined criterion as proposed in previous section should be used instead. It is also observed that the 5% ovality give quite different performance between "open" and "close" mode. In "open" mode, it gives almost the largest capacities. But in "close" mode, it represents the minimum capacities for bend under external pressure loads. In this respect, it is very important to check the ovality for the bend in "close" mode, especially when the bend is under external pressure loading, such as the "shut down" case during the spool pipeline's service life.

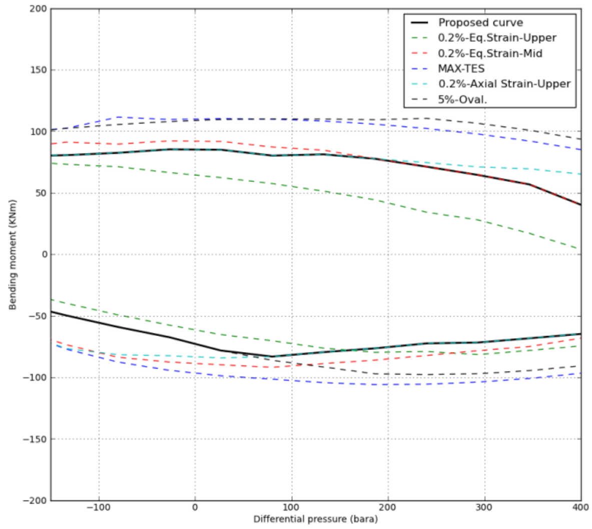

FIG. 9 CAPACITY CURVES BASED ON DIFFERENT CRITERIA OF 90 DEG BEND FOR 6" MEG SPOOL WITH MAT1

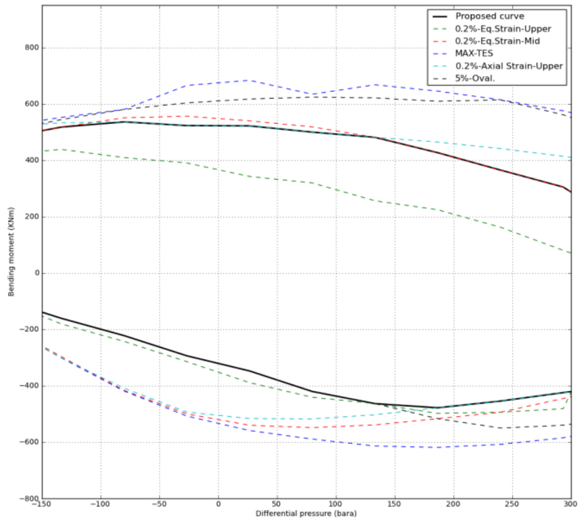

FIG. 10 CAPACITY CURVES BASED ON DIFFERENT CRITERIA OF 90 DEG BEND FOR 12" PRODUCTION SPOOL WITH MAT1

Fig. 10 presents the capacity curves for 12" production spool bends. Similar conclusions can be observed as Fig. 9. The 5 % ovality curve in "close" mode shows

the most conservative capacities in most cases. It may be a hint that the bend is easier to deform under “close” mode with external pressure loading if the outer diameter is larger. However, more numerical simulation cases are needed before any general conclusions are made in this respect.

Discussion

Initial Ovality

The initial ovality applied to the local numerical model is an important factor. As concluded by Torselleti (2000), the maximum 3 % initial ovality can be applied for straight pipeline according to international standards in deep water areas. As to the pipe bend, the actual ovality is highly dependent on the bend fabrication method, as well as the ovality of the mother bend pipe.

Experience has shown that the capacity of the bend will be much influenced by the initial ovality if the upper strain based criterion is used. The reason to this is that the local mechanism as mentioned before dominates the strain at outer fibber of the bend, especially when the internal pressure is relatively high. However, with present new combined criterion, the capacity curve is less influenced by the initial ovality applied to the finite element model, especially for the 6” MEG spool case; see Fig. 11. The big differences are located at the “close” mode when the differential pressure is negative. In this case, the spool bend is subjected to outer pressure and closing moment both have the tendency to increase the ovality of the spool bend. In general, this is always the “worst” loading case for spool bend. And it can be concluded that the higher initial ovality, the lower capacity the bend will have in the “close” mode with internal pressure loads. One interesting observation here is that the ovality shows opposite influence to the bending capacity in the left and right side of the capacity curve figure. This is due to the fact that “open” force and the internal pressure are both trying to smooth the pipe initially, which is exactly the opposite mechanism in “close” mode with external pressure.

The same observations are obtained from the results of 12” production spool; see Fig. 12. However, it is seen that the capacity curve for 12” spool was more influenced by the ovality comparing to 6” MEG spool. And it is noticed that the 30 degree bend of 12” production spool is quite sensitive to the ovality in the “close” mode with external pressure. Special attention should be paid to this “worst” case during the capacity check, where the capacity problem may arise.

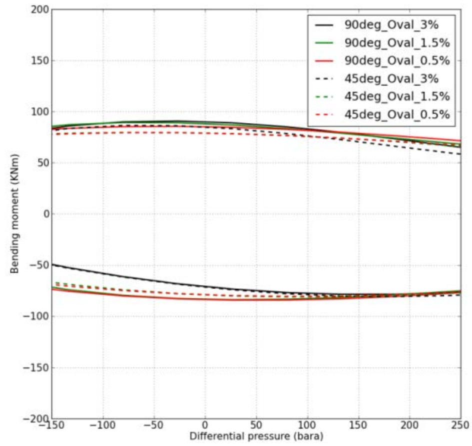

FIG. 11 OVALITY INFLUENCE TO BEND CAPACITY FOR 6” MEG SPOOL (FITTED CURVES)

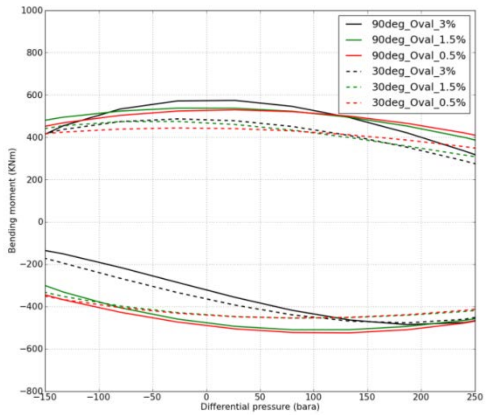

FIG. 12 OVALITY INFLUENCE TO BEND CAPACITY FOR 12” PROD SPOOL (FITTED CURVES)

Wall Thickness

A check for the influence of wall thickness to the bend capacity was done for 6” MEG spool; see Fig. 13. Obviously, the increase of wall thickness ends up with higher bending capacities. The difference is big especially when the internal/external pressure is significant large in both “open” and “close” modes.

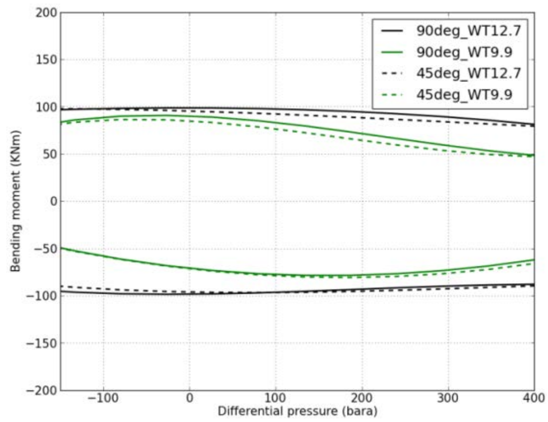

FIG. 13 WALL THICKNESS INFLUENCE TO BEND CAPACITY FOR 6” MEG SPOOL (FITTED CURVES)

On the other side, a thinner wall thickness will decrease the bending capacity for the bend. Thus, it is important to check the bend's capacity by including the negative fabrication tolerance and also the corrosion tolerance thickness for the bend. It may happen that the capacity check is not fulfilled by doing this, and then additional remedies should be made accordingly.

Global Model

General

The global numerical model has been analyzed by ANSYS 13, which is a general purpose finite element code (ANSYS, 2010). The actual seabed profile is implemented. Kinds of tolerances, such as metrology tolerance, installation tolerances etc. were included in different loading cases through the whole analysis; see Fig. 15. The actual loading for spool bends will be summarized based on the results from global analyses.

An example of summarized loads for 6" MEG spool bends are presented in Table 2. Notice that the bend has different capacities in "open" and "close" modes. M_t is the resultant moment calculated as Eq. 2, which is treated as the actual moment loading for pipe bend.

$$M_t = \sqrt{M_x^2 + M_y^2 + M_z^2} \tag{2}$$

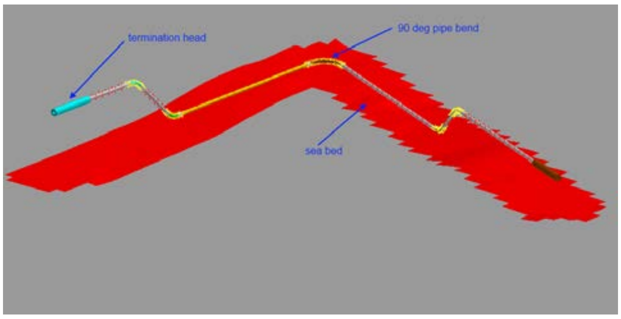

FIG. 14 GLOBAL SPOOL TIE-IN FINITE ELEMENT MODEL IN ANSYS 13

TABLE 2 AN EXAMPLE LOADS FR BEND FROM GLOBAL MODEL, 6" MEG SPOOL

Case	Pre. [Bara]	Mx. [kN]	My. [kN]	Mz. [kN]	Mt [kN]	Mode
Initial	0.1	0	30.6	0.1	30.6	close
Stroke2	0.1	0	27.2	9	28.65	close
Align2	0.1	0	26.8	8.9	28.24	close
Stroke1	0.1	-0.4	21.2	-3.1	21.43	close
Align1	0.1	4.6	15.8	-1	16.49	open
PRES	276.3	4.6	15.7	-1	16.39	open
OP	259	4.6	15.5	-1	16.2	open
SD	-85	4.6	15.9	-0.4	16.56	open
DEP	-85	4.3	15.6	-1.6	16.26	open

It has to be pointed out that the spool bends are generally under mixed in-plane and out-of-plane moment loadings; see Table 2. However, only in-plane moment loading is considered in the local finite element model in present study. To cope with this simplification, the resultant moment M_t is used as the actual in-plane bending moment. Based on Karamanos et. al (2006), it is conservative to neglect the out-of-plane moment in "close" mode while it is a question in "open" mode, which should be further investigated in future work.

Spool Bend Capacity Check

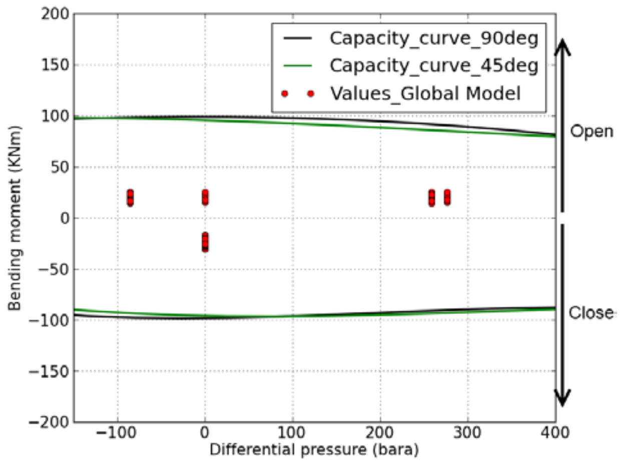

FIG. 15 BEND MOMENT CAPACITY CURVES TOGETHER WITH VALUES FROM GLOBAL MODEL,6" MEG SPOOL (FITTED CURVES)

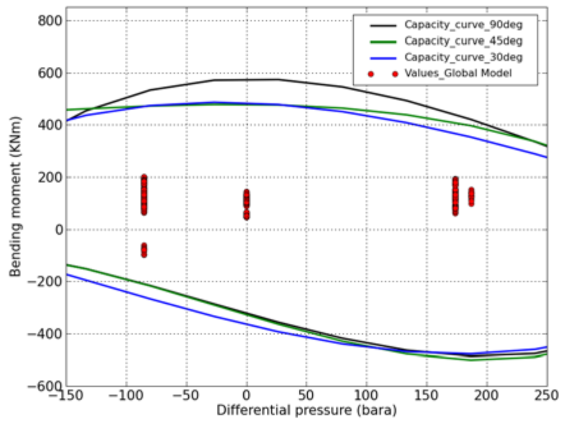

FIG. 16 BEND MOMENT CAPACITY CURVES TOGETHER WITH VALUES FROM GLOBAL MODEL, 12" PRODUCTION SPOOL (FITTED CURVES)

Two bend angles (90º and 45º) are modelled in the numerical LS-DYNA model based on the MEG spool geometry. As seen from Fig. 15, there are sufficient safety margin comparing to those bending moments from the global numerical model. The worst utilization

factor is 0.31. Additional check has also been done by considering the negative fabrication tolerance to the thickness of the bend, no critical issues are observed.

The same method has also been applied to the capacity check to 12″ production spool; see Fig. 16. Three different bend angles are simulated in the local model according to the spool geometry. And again, the spool is within capacity range.

Conclusions

The design practice of bending capacity assessment to 6″ and 12″ pipeline spool bends are presented in this paper. Following conclusions are summarized:

- A comparative study on different design criteria for assessing bending capacities has been performed;
- A combined design criterion is concluded to assess the bending moment capacities for spool bends. This criterion includes sufficient safety margin and acceptable imposed ovality;
- The local and global finite element models are combined together to access the bending capacity for spool bends under deep water;
- The local mechanism of pipeline bends under both in-plane moment and internal/external pressure loadings are discussed in detail. The local reshape mechanism occurs especially when the internal pressure loading is significant;
- Sensitivity studies regarding the initial ovality have been presented. It is observed that the bends of 12″ pipeline spool are more influenced by the initial ovality comparing to those of 6″. In general, higher initial ovality yields lower bending capacity in the "worst" loading case;
- The increased wall thickness of bend will increase the bending capacity.

As mentioned previously, the investigation of out-of-plane moment influences to the bending capacity of pipeline bends should be performed, especially for the "open" mode. Nevertheless, the presented capacity assessment method.

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